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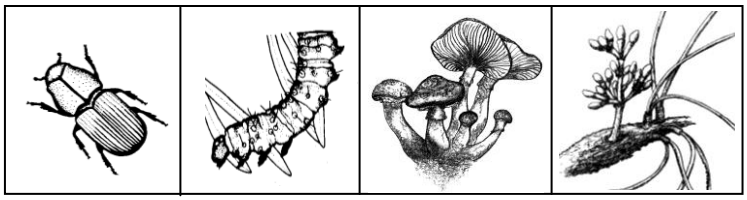

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Performance of Rust-Resistant Western White Pine in Operational Plantations in Northern Idaho: 1995-2006

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INTRODUCTION

Arrival & impact of white pine blister rust

Western white pine (*Pinus monticola* Dougl. ex D. Don) was once a dominant species on over five million acres of the Inland Northwest but now represents the cover type on less than 5% of its historic range (Neuenschwander et al. 1999, Fins et al. 2001, Harvey et al. 2008). This dramatic reduction resulted from factors such as selective harvest, mortality due to mountain pine beetle (*Dendroctonus ponderosae* Hopkins), and lack of natural regeneration due to fire exclusion. The primary cause, however, was the introduction of *Cronartium ribicola* J.C. Fisch., a non-native pathogen that causes white pine blister rust (WPBR) of five-needled pines. The pandemic caused by WPBR decimated western white pine across much of its native range, altering species composition and successional processes such that shade-tolerant species became much more dominant. This resulted in a loss of ecosystem function and diversity, as well as an increase in losses due to pathogens and insects to which shade-tolerant species are often more susceptible (Byler and Hagle 2000, Harvey et al. 2008, Samman et al. 2003, Schwandt 2000).

The introduction of *C. ribicola* to western North America has long thought to have been a one-time occurrence when a shipment of infected eastern white pine (*Pinus strobus* L.) seedlings were transported in 1910 from a nursery in France to Point Grey, British Columbia (Mielke 1943). An argument has recently been

made, however, that historical evidence suggests at least a handful of separate introductions could easily have occurred in western North America (Hunt 2010). In either case, *C. ribicola* had been recognized prior to its introduction as a grave threat to North American five-needled pines based on the severity of damage in nurseries and commercial plantations of various species, particularly eastern white pine, in western Europe (Spaulding 1922). Unfortunately these concerns did not halt continued shipments of WPBR-susceptible, five-needled pine species from European nurseries to both eastern and western North America. A quarantine on seedling imports to western North America was imposed in 1914 but, in addition to evidence that it was not strictly observed (Hunt 2010), it was already too late.

The presence of WPBR in the region around Vancouver, British Columbia was not detected until 1921, by which time it had already spread from infected eastern white pines into horticultural and native *Ribes* spp. (alternate hosts for *C. ribicola*) and from there into native stands of western white pine (Mielke 1943). Due to efficient, long-distance spread by the aerially-dispersed aeciospores of *C. ribicola* from infected pines to *Ribes* spp. each spring, the fungus spread to the east and southeast with prevailing winds and entered the white pine zone of northern Idaho and western Montana in the early- to mid-1920's (Lachmund 1926, Mielke 1943, Pennington 1925). The damage from WPBR was severe in all age classes of western white pine. Small trees were killed relatively quickly by girdling once *C. ribicola* branch cankers reached the stem; the crowns of large trees often suffered hundreds of individual branch infections that severely impacted vigor before overwhelming the tree (Lachmund 1934).

Attempts at WPBR control began as soon as it was realized that the disease would inevitably spread across the Inland Northwest. Eradication of *Ribes* spp., chemical treatment of cankers, and biological control efforts using native fungi were all attempted to various degrees from the 1920s into the 1960s, but were eventually abandoned as unfeasible (Ketcham et al. 1968).

White pine breeding program

As early as the late 1920s, non-infected, or infected but surviving, western white pine were observed in Idaho and Montana forests originally composed of a high proportion of western white pine that had otherwise been decimated by WPBR (Bingham 1983, Hartley 1927). This raised hopes there was some level, however low, of natural resistance to WPBR in the native western white pine population. In 1950, USDA Forest Service (USFS) scientists formalized the rust-resistance breeding program for western white pine in the Inland Empire to test for natural, heritable resistance to *C. ribicola*.

Surveys were conducted to identify non-infected western white pine in stands long-exposed to WPBR. Controlled pollinations among all pairs of rust-free selections in the field enabled selection of the parent trees used to establish the first generation (F_1) seed orchard at Sandpoint, ID (Bingham et al. 1963). F_1 parents with demonstrated resistance were then used to establish seed orchards where cross-breeding via wind pollination produced seed of potentially rust-resistant, second generation (F_2) stock (Bingham et al. 1953, Bingham 1983). There have been three "phases" in selecting apparently resistant parent trees to incorporate into the breeding program (Hoff 1977, Howe and Smith 1994, Mahalovich

2010). Testing of parent trees to determine their rust-resistant status and potential inclusion in the breeding program is an ongoing process (Mahalovich 2010).

Early, artificial-inoculation tests in a nursery setting found that 66% of F_2 seedlings were rust-free after two and a half years (Hoff et al. 1973). The long-term expectation was for 65% or greater survival of this F_2 stock when grown under natural stand conditions (Bingham 1983). However, artificial screening only allows detection of resistance mechanisms at early ages and cannot evaluate long-term field effectiveness (Yanchuk et al. 1994).

As F_1 and then F_2 stock became available beginning in the late 1970s, it was outplanted extensively onto private, state, and federal lands in northern Idaho and western Montana (Fins et al. 2001, Muller 2002). There was, however, no systematic, long-term monitoring of performance put in place for these operational plantings (Mathiasen and Schwandt 1993). Data from early test plantations containing various western white pine stock types, ranging from natural seed sources (also known as "wild" or "woodsrun") to F_2, indicated that survival of F_2 might be greater than originally expected (Goddard et al. 1985). However, by the early 1990s, anecdotal reports gave rise to concerns that improved stock on sites with high rust hazard may not be performing as well as expected.

Subsequently, the USFS and the Idaho Department of Lands (IDL) cooperated in establishing permanent plots in operational western white pine plantations in order to evaluate the field performance of western white pine stock types (Figure 1) (Mathiasen and Schwandt 1993). The objectives were to monitor both WPBR infection levels and long-term survival in operational F_1 and F_2 plantations. This report details the findings of this monitoring effort for the period from 1995 to 2006.

METHODS

The original study plan specified plantation-selection criteria, sampling design, plot installation, baseline data collection, and methods of monumenting plantations, plots, and individual trees (Mathiasen and Schwandt 1993 - Appendix A). A total of 15 IDL plantations and seven USFS plantations were selected for monitoring; all 22 are located in northern Idaho between Orofino and the Canadian border (Figure 1).

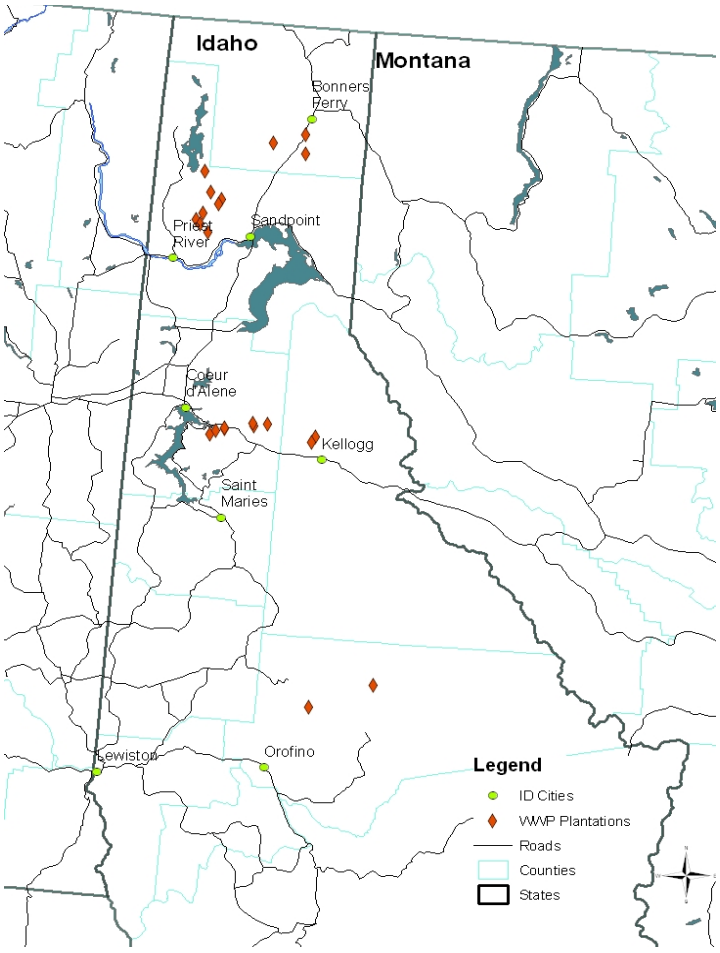

Figure 1. Locations of western white pine plantations.

Young plantations, ranging in age from newly planted to nine years old, were selected in order that planted seedlings could be more readily distinguished from natural regeneration, as well as to accurately monitor and diagnose WPBR infection and mortality from a relatively early age (Figure 2). Only 13 of the IDL plantations are reported on here as plots were not installed in two plantations until the fall of 2000 (Table 1).

The study plan called for coordinated remeasurements of all plots at approximately three to five year intervals (Mathiasen and Schwandt 1993). However, due to changes in personnel, budgeting and scheduling problems, as well as other factors, neither the timeline for installing plots nor the desire to perform concurrent remeasurements on all plots within the same year could be met. We therefore chose to report here only on data from 1995, 2000, and 2006, as these were years when data were collected in all 20 plantations. Data from the two IDL plantations where plots were installed in 2000 can be included in future analyses of all 22 plantations.

Figure 2. Copper Gimlet 21 plantation at the time of permanent plot installation.

Data collection consisted of careful examination, branch-by-branch and along the stem, for evidence of WPBR. As long as tree height was less than approximately eight feet, a tree could be examined carefully in its entirety. As trees grew in height, however, the upper branches could not be examined as closely as lower branches, until finally the uppermost branches could not be examined at all. The upper crowns of such trees were still scanned visually for evidence of WPBR infection, but early diagnosis of infections became much more difficult and new infections might go undetected for several years until symptoms such as a dead branch, swollen branch canker, or rodent chewing around a canker could be seen.

The analysis for percent infection within a plantation is based on the presence of at least one identifiable canker anywhere on a tree. Interactions between F_2 stock and *C. ribicola* can make diagnosis of basal deformations of tree stems problematic (Eckert 2007). In our study, basal deformation was generally attributed to the presence of a WPBR basal canker whose normal growth had been affected by a resistance mechanism, to the effects of root disease, or to physical damage. Questionable infections were examined closely, and the technique of wetting and brushing the bark surface around cankers was employed frequently to look for diagnostic yellow-orange canker margins. In cases where infection was suspected but could not be confirmed to our satisfaction, the location of the suspect infection was carefully noted so it could be re-examined during subsequent remeasurements. Long-term monitoring proved invaluable as it allowed us to observe instances where WPBR canker margins "broke out," or began obvious growth, from areas that previously could not

Table 1. Summary of 20 western white pine plantations in northern Idaho.

Plantation	Ownership[1]	Year Planted	Plots Estab.[2]	WP Stock[3]	Planted Trees[4]	Natural Regen[5]
All the Way	IDL	1984	1991	F_2	95	1
Big Foxy	IDL	1993	1995	F_2	103	1
Blue Creek	IDL	1993	1995	F_2	99	0
Contrary Creek	IDL	1993	1993	F_2	89	13
Copper-Gimlet 1	USFS	1986	1992	F_2	174	29
Copper-Gimlet 2	USFS	1986	1992	F_2	61	16
Copper-Gimlet 21	USFS	1984	1992	F_2	164	116
Happy Blue	IDL	1993	1995	F_2	98	0
Keokee Creek	IDL	1985	1993	F_2	223	4
Lost Cat	IDL	1993	1995	F_2	112	0
Lost Jungle	IDL	1993	1995	F_2	77	2
Paradise Valley	IDL	1985	1991	F_2	111	2
POL 92 - A	IDL	1992	1993	F_2	88	88
Remas	IDL	1994	1995	F_2	99	5
Uleda Creek	IDL	1992	1995	F_2	114	0
Varnum 11	USFS	1989	1992	F_2	106	12
Varnum 2	USFS	1988	1992	F_1	116	107
Varnum 23a	USFS	1988	1992	F_1	129	28
Varnum 23b	USFS	1988	1992	F_2	111	57
Waters Creek	IDL	1985	1995	F_2	136	3

[1] Ownership: IDL = lands managed by Idaho Department of Lands, USFS = lands managed by the USDA Forest Service
[2] Plots Established = year in which permanent plots were established within plantation.
[3] Western white pine stock type.
[4] Number of planted, rust-resistant western white pine within all plots.
[5] Number of naturally regenerated western white pine within all plots.

be diagnosed with any certainty as being WPBR.

Live trees could not be destructively sampled to diagnose suspected root disease, so trees that died between remeasurements were closely examined to assign a primary cause of mortality whenever possible. Rust-caused mortality was recorded if a tree's stem had been girdled by a WPBR canker even though there may have been evidence of simultaneous root disease infection. We also noted evidence of secondary bark beetles, weevils, wood borers, bear girdling (bark feeding), livestock trampling, snow damage, suppression, drought, and inadvertent removal. In cases where we could not confidently assign a cause, mortality was categorized as unknown.

Statistical analyses were performed using the SAS statistical program (version 9.1, SAS Institute Inc., Cary, North Carolina). Analysis of variance with Tukey's honest significant difference (HSD) was used for multiple comparisons of means. Analyses

Table 2. Cumulative white pine blister rust infection of rust-resistant stock and natural regeneration by measurement year.

		Planted			Natural		
Plantation	**Stock**	**1995**	**2000**	**2006**	**1995**	**2000**	**2006**
All the Way	F_2	0	0	5.3	[1] ---	---	---
Big Foxy	F_2	0	7.8	25.5	---	---	---
Blue Creek	F_2	0	7.1	25.3	---	---	---
Contrary Creek	F_2	0	0	0	0	0	0
Copper-Gimlet 1	F_2	39.1	49.4	67.2	37.9	72.4	82.8
Copper-Gimlet 2	F_2	13.1	45.9	45.9	37.5	87.5	87.5
Copper-Gimlet 21	F_2	35.4	45.7	47.0	17.2	59.5	67.2
Happy Blue	F_2	0	29.6	42.9	---	---	---
Keokee Creek	F_2	33.6	40.4	48.4	---	---	---
Lost Cat	F_2	0	23.2	42.0	---	---	---
Lost Jungle	F_2	0	14.3	26.0	---	---	---
Paradise Valley	F_2	0.9	0.9	4.5	---	---	---
POL 92 - A	F_2	0	8.0	22.7	0	29.5	56.8
Remas	F_2	0	29.3	53.5	---	---	---
Uleda Creek	F_2	0	11.4	29.8	---	---	---
Varnum 11	F_2	1.9	23.6	29.2	0	66.7	75.0
Varnum 2	F_1	63.8	84.5	88.8	83.2	95.3	95.3
Varnum 23a	F_1	56.6	84.5	91.5	17.9	92.9	96.4
Varnum 23b	F_2	2.7	40.5	51.4	3.5	64.9	64.9
Waters Creek	F_2	49.3	75.7	83.8	---	---	---
Total Trees		2305	2305	2304	484	484	484
Percent Infected	F_1	60.0	84.5	90.2	28.3	63.6	72.1
Percent Infected	F_2	13.7	28.3	39.3			

[1] --- indicates either no natural regeneration recorded within plots or sample size less than 10.

of variance in WPBR incidence and survival by measurement year were run with a mixed linear model permitting correlation and non-constant variability (Proc Mixed) using plantation as a random effect. Disease incidence was calculated as the number of WPBR infected trees per number of evaluated trees per plantation. Once a tree was diagnosed with a WPBR canker it was categorized as infected from then on unless the diagnosis proved inaccurate in subsequent measurements. Incidence of WPBR across remeasurement periods was therefore a cumulative measure of the infection level. Only those trees monumented on permanent plots prior to or in 1995 were used to analyze blister rust infection levels and mortality between 1995 and 2006.

RESULTS

Table 1 provides a summary of the 20 western white pine plantations monitored for

Table 3. Average annual rate of increase in white pine blister rust infected trees in 20 western white pine plantations in Northern Idaho by measurement period.

		Average annual rate (%) of new infections					
		Planted			Natural		
Plantation	**Stock**	**95 - 00**	**00 - 06**	**95 - 06**	**95 - 00**	**00 - 06**	**95 - 06**
All the Way	F_2	0.0	0.9	0.5	---	---	---
Big Foxy	F_2	1.6	3.0	2.3	---	---	---
Blue Creek	F_2	1.4	3.0	2.3	---	---	---
Contrary Creek	F_2	0.0	0.0	0.0	0.0	0.0	0.0
Copper-Gimlet 1	F_2	2.1	3.0	2.6	6.9	1.7	4.1
Copper-Gimlet 2	F_2	6.6	0.0	3.0	10.0	0.0	4.5
Copper-Gimlet 21	F_2	2.1	0.2	1.1	8.4	1.3	4.5
Happy Blue	F_2	5.9	2.2	3.9	---[1]	---	---
Keokee Creek	F_2	1.3	1.3	1.3	---	---	---
Lost Cat	F_2	4.6	3.1	3.8	---	---	---
Lost Jungle	F_2	2.9	1.9	2.4	---	---	---
Paradise Valley	F_2	0.0	0.6	0.3	---	---	---
POL 92 - A	F_2	1.6	2.5	2.1	5.9	4.5	5.2
Remas	F_2	5.9	4.0	4.9	---	---	---
Uleda Creek	F_2	2.3	3.1	2.7	---	---	---
Varnum 11	F_2	4.3	0.9	2.5	13.3	1.4	6.8
Varnum 2	F_1	4.1	0.7	2.3	2.4	0.0	1.1
Varnum 23a	F_1	5.6	1.2	3.2	15.0	0.6	7.1
Varnum 23b	F_2	7.6	1.8	4.4	12.3	0.0	5.6
Waters Creek	F_2	5.3	1.3	3.1	---	---	---
Average Annual Increase	F_1	4.9	0.9	2.7	8.7	0.3	4.1
Average Annual Increase	F_2	3.1	1.8	2.4	8.1	1.3	4.4

[1] --- indicates either no natural regeneration recorded within plots or sample size less than 10.

WPBR infection and mortality. Eighteen of the 20 plantations had been planted with F_2 western white pine stock and two with F_1 stock. Data were collected over the three measurement periods on a total of 2789 western white pine: 2060 F_2, 245 F_1, and 484 naturals.

Incidence of White Pine Blister Rust

In 1995, the infection level of all improved stock was 13.7% for F_2 and 60.0% for F_1, compared to 28.3% of the natural regeneration (Table 2). While this would seem to show that the F_1 stock was becoming infected at a higher level than natural regeneration, a closer look reveals that within the two plantations of F_1 stock the natural regeneration had a higher level of infection (69.6%) compared to the F_1 (60%) (Figure 4). Within individual plantations the incidence of WPBR ranged from 0 – 49.3% of F_2 stock, 56.6 – 63.8% of F_1 stock, and 0 – 83.2% of the natural regeneration.

By 2000, the incidence of WPBR had increased in the improved stock to 28.3% of F_2 and 84.5% of F_1 (Table 2). In comparison, 63.6% of all natural regeneration was infected: 51.6% in the 18 F_2 plantations and 94.8% in the two F_1 plantations (Figures 3 and 4). Incidence of WPBR within individual plantations ranged from 0 – 75.7% for F_2 stock, 84.5% for F_1 stock, and 0 – 95% for natural regeneration.

By 2006, 39.3% of all F_2 stock was infected by WPBR, compared to slightly more than 90% of the F_1 stock. In comparison, 72% of all natural regeneration was infected: 63% in the 18 F_2 plantations and nearly 96% in the two F_1 plantations (Figures 3 and 4). Infection within plantations varied from 0 – 67% of F_2, 89 – 91.5% of F_1, and 0 – 100% of naturals. The plantations with the highest incidence of infection were not just those that had been exposed the longest (i.e. the oldest plantations, Table 1). For example, one of the oldest plantations, All the Way, had a low cumulative WPBR infection of 5.3% in 2006. In comparison the youngest plantation, Remas, which was planted 10 years later than All the Way, had a cumulative WPBR infection of 53.5% by 2006 (Table 2).

Between 1995 and 2000, the average annual rate of newly-infected, planted stock ranged from 0 – 7.6% (Table 3) in the 18 F_2 plantations, with an average of 3.1%. This means that, on average, approximately 3% of previously uninfected F_2 stock became infected each year. In seven of the 18 F_2 plantations the average annual rate of newly-infected stock increased throughout the second measurement interval (2000 – 2006), in nine it declined, and in two it remained the same. From 2000 – 2006, the average annual rate of newly-infected stock across all 18 F_2 plantations decreased to 1.8%, with a range of 0 – 4.0%. Over the entire 11-year measurement interval encompassed by this report the average annual rate of increase in newly-infected F_2 stock across all 18 plantations was 2.4%, with a range of 0 – 4.9%. If the infection rate remained constant at 4.9% it would take just over 20 years for all trees within a plantation to become infected, or just over 40 years at the average 2.4% annual infection rate.

The infection levels for the nine plantations that had reached age 17-22 during the 11-year monitoring period are presented in Figure 5. While this displays only half of the plantations, many different trajectories can be observed. Infection rates in two plantations appear to be leveling off (Copper-Gimlet 2 and 21), three are slowing down (e.g. - Varnum 11 and 23b), one remained relatively constant (Keokee Creek), and three increased (e.g. - Copper-Gimlet 1) through the age increment.

Mortality

As WPBR infection levels increased from 1995 to 2006, so too did mortality of both improved stock types and the natural regeneration, although not all mortality was due to WPBR. In 1995, 86.8% of all western white pine were alive; the mortality was attributed to WPBR (81.3%), root disease (4.3%), and "other causes" (14.4%) (Table 4). In 1995, the F_1 stock had higher mortality (26.5%) due to WPBR than did the F_2 stock (7.9%) stock (Figures 3 and 4). Natural regeneration in the F_1 plantations had higher mortality due to WPBR (34.8%) than natural regeneration in the F_2 plantations (7.2%).

By the year 2000, overall survival had dropped to 65.3%, with 79.5% of mortality attributed to WPBR, 8.1% to root diseases, and 12.4% to other causes. Among the 18 F_2 plantations WPBR-caused mortality of

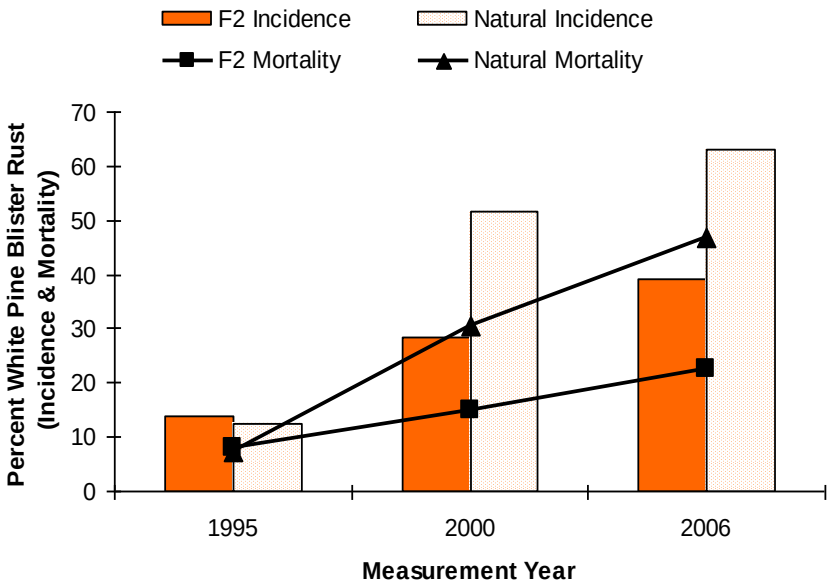

Figure 3. Cumulative white pine blister rust incidence and mortality due to white pine blister rust in 18 F_2 western white pine plantations in northern Idaho.

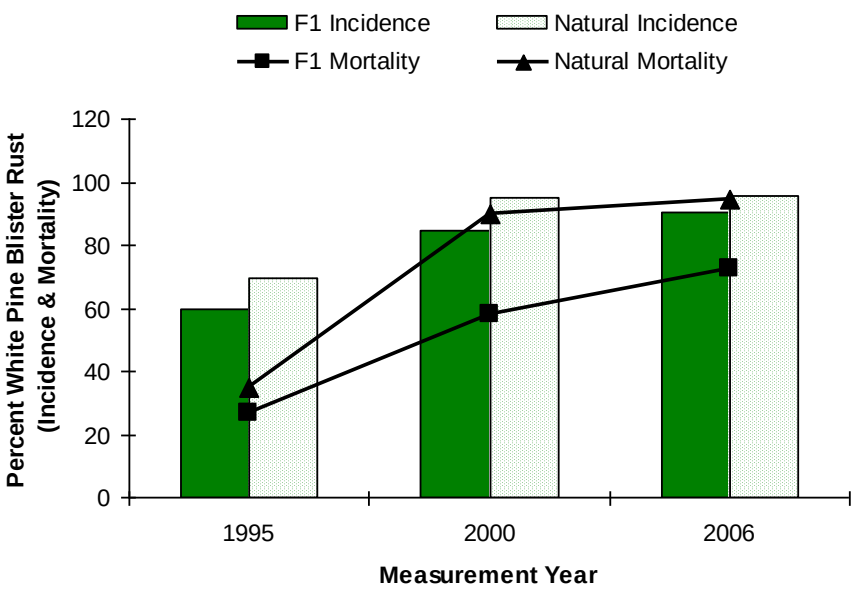

Figure 4. Cumulative white pine blister rust incidence and mortality due to white pine blister rust in two F_1 western white pine plantations in northern Idaho.

Table 4. Western white pine condition by measurement year and stock type.

		1995					2000					2006				
				Cause of death					Cause of death					Cause of death		
		Alive	Missing	WPBR	RD	Other	Alive	Missing	WPBR	RD	Other	Alive	Missing	WPBR	RD	Other
F_2	Number	1837	1	162	16	44	1504	103	307	57	89	1256	77	461	117	149
	Percent	89.2	0.0	7.9	0.8	2.1	73.0	5.0	14.9	2.8	4.3	61.0	3.7	22.4	5.7	7.2
F_1	Number	178	0	65	0	2	94	2	142	4	3	49	2	177	8	9
	Percent	72.7	0.0	26.5	0.0	0.8	38.4	0.8	58.0	1.6	1.2	20.0	0.8	72.2	3.3	3.7
Natural	Number	405	0	72	0	7	224	12	227	8	13	125	15	276	16	21
	Percent	83.7	0.0	14.9	0.0	1.4	46.3	2.5	46.9	1.7	2.7	27.6	3.3	60.9	3.5	4.6
Total	Number	2420	1	299	16	53	1822	117	676	69	105	1430	94	914	141	179
	Percent	86.8	0.0	10.7	0.6	1.9	65.3	4.2	24.2	2.5	3.8	51.8	3.4	33.1	5.1	6.5

Cause of death: WPBR = white pine blister rust, RD = root disease, Other = Bear girdling, cutting, Ips bark beetles, weevils, suppression, and unknown causes.

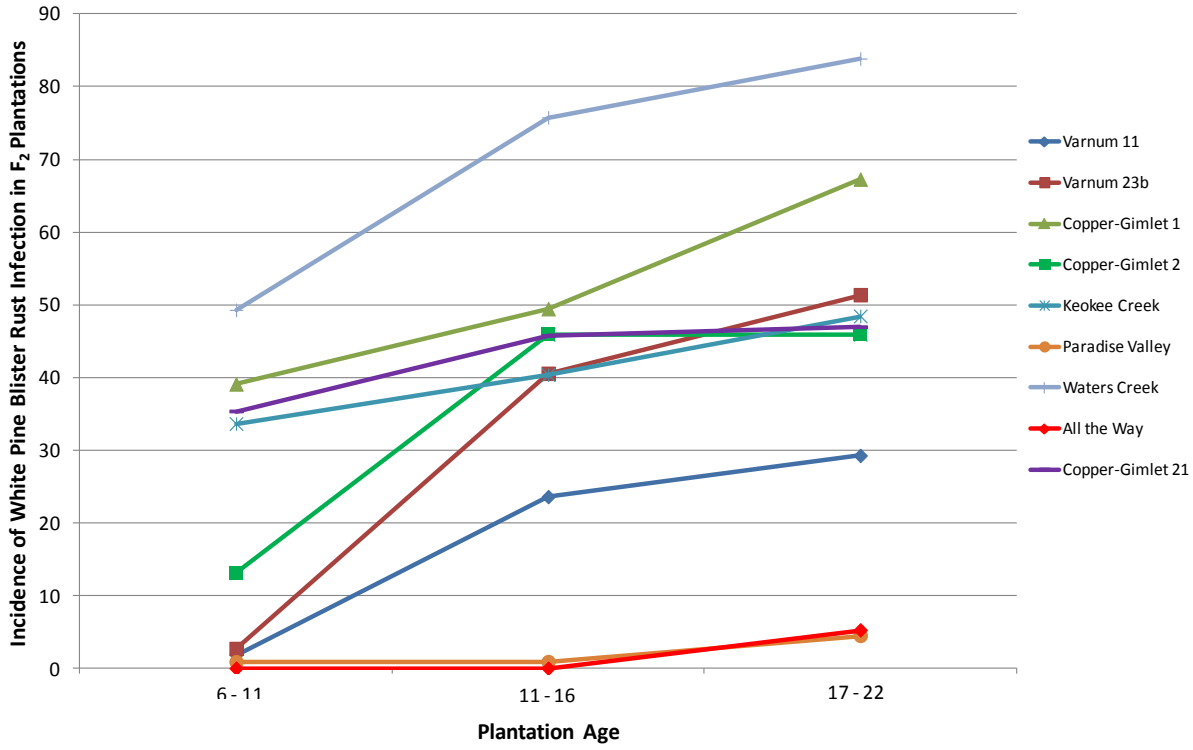

Figure 5. White pine blister rust incidence by plantation age in nine F_2 western white pine plantations in northern Idaho.

natural regeneration was greater than 30%, compared to less than 15% in the F_2 stock (Figure 3). In the two F_1 plantations, 58% of improved stock was dead due to WPBR in 2000, compared to almost 90% of the natural regeneration (Figure 4).
By 2006, 51.8% of the original 2789 trees (2060 F_2, 245 F_1, and 484 naturals) remained alive. Of the mortality that occurred 74.1% was due to WPBR and 11.4% to root disease. The F_2 stock continued to perform far better than either the F_1 stock or natural regeneration. F_2 stock experienced 22.4% mortality due to WPBR compared to over 72% of the F_1 stock. Natural regeneration in the F_2 plantations experienced 46.9% mortality due to WPBR while that in the F_1 plantations was 94.7% (Figures 3 and 4).

While the probability of survival declined over time, in every measurement period F_2 stock had a significantly higher probability of survival than did either the F_1 stock or natural regeneration. For example, in 2000 the probability of a tree being alive was 0.77 for the F_2 compared to 0.39 for the F_1 and 0.47 for natural regeneration. By 2006, probability of survival in the F_2 had declined to 0.63, but this was still significantly higher than that of either the F_1 (0.20) or the natural regeneration (0.28).
Mortality due to WPBR since 1995 was significantly higher for F_2 stock that was infected in 1995 than for trees not infected in 1995. The probability of death from any cause for F_2 stock infected with WPBR in 1995 was 0.82 in 2000 and 0.95 in 2006; this compares to trees without WPBR infections in 1995 which had a 0.19 and 0.29 probability of mortality from any cause in 2000 and 2006, respectively. Similarly, F_2 stock diagnosed with WPBR by 2000 had a significantly higher probability of being

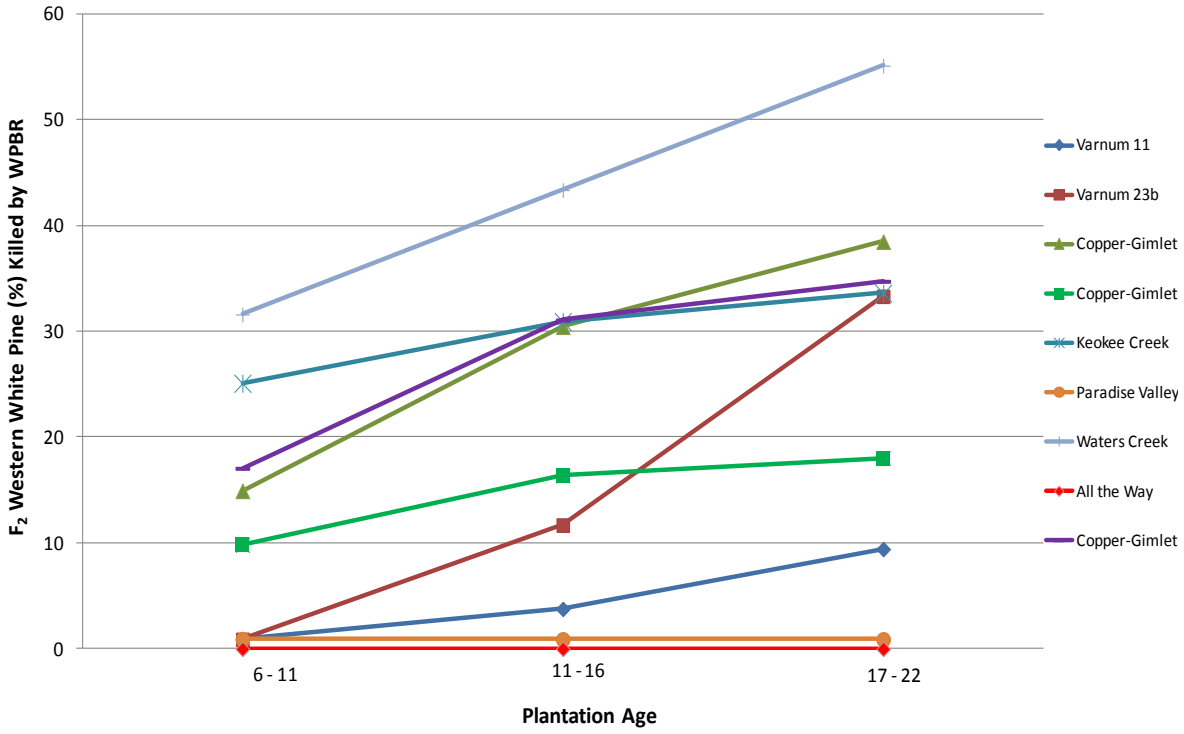

Figure 6. Mortality due to white pine blister rust by plantation age in nine F_2 western white pine plantations in northern Idaho.

dead in 2006 (0.82) than F_2 stock not infected with WPBR in 2000 (0.19).

The effect of plantation, or site, on incidence of WPBR and the condition of the planted stock (live or dead) in each measurement year was significant. The two F_1 plantations consistently had the highest level of infection among all 20 plantations, and the incidence of WPBR was significantly higher in these than all F_2 plantations except Waters Creek (Table 2). Mortality rates were highest among the two F_1 plantations and Waters Creek in every measurement year. When the effect of site was removed the F_2 stock had significantly lower incidence of WPBR than did the F_1 stock or the natural regeneration after 11 years of monitoring. By 2006, there were statistically significant differences between all stock types in terms of survival. The F_2 had the highest probability of survival (0.62), the F_1 had a moderate probability of survival (0.45), and the natural regeneration had the lowest probability of survival (0.34).

Mortality levels by plantation and plantation age are presented in Figure 6. Although no plantations at age 6-11 had mortality rates greater than 33%, by age 17-22 five of nine plantations had over 33% mortality.

DISCUSSION

Studies have documented the intensification of WPBR through time in various species of naturally regenerated, five-needled pines (e.g., Conklin 2004, Fracker 1936, Lachmund 1934). The current study documents increasing WPBR incidence in first (F_1) and second (F_2) generation,

improved western white pine stock. In 1995, ten of the plantations had no WPBR infection in F_2 stock and three had an incidence of less than 3%. Eleven years later only one plantation, Contrary Creek, remained rust-free and only one plantation with WPBR had an incidence less than 5%. Incidence of WPBR in the F_2 stock increased from 13.7 to 39.3% over the 11-year measurement period, compared to an increase from 12.3 to 63.0% in the natural regeneration within the same plantations (Figure 3). During this 11-year monitoring period, F_2 stock out-performed both the natural regeneration and F_1 stock.

It is not safe to assume, however, that based on early performance there will be little damage in the future. While infection levels were low or zero in many of the F_2 plantations in 1995 when the planted trees were between 2 and 12 years of age, results from this study show incidence can increase rapidly. It is imperative, therefore, that forest managers plan to periodically survey WPBR infection levels in F_2 plantations to determine if intermediate activities, particularly pruning, are necessary to meet management objectives (Schnepf and Schwandt 2006, Schwandt and Ferguson 2003).

Land managers often ask if there is an age at which they can assess the level of WPBR infection of western white pine and project the future infection level through the life of the plantation. Our data indicates this may be difficult because infection rates in some plantations declined while others increased during the 11-year monitoring period (Figure 5). White pine blister rust may be removing the most susceptible trees from these plantations. If so, we would expect rust incidence and mortality to level off over time as the most susceptible trees become infected and die. Overall incidence of WPBR among the F_2 stock increased 14.6% from 1995 to 2000 and 11% from 2000 to 2006. However, that rate of change varied greatly between plantations with some having an increase in incidence greater than 24% during the 2000 - 2006 interval. Initial reports from artificial inoculations of F_2 seedlings suggested that rust incidence would not exceed 33% (Hoff et al. 1973), and field tests suggested that they may perform even better under natural conditions (Bingham et al. 1973, Steinhoff 1971). However, studies in other areas indicated that actual infection was often much higher (Hunt and Meagher 1989). A northern California study that monitored Idaho F_2 stock for more than 30 years showed relatively steady infection and mortality curves that culminated in 36 - 56% infection 22 years post-planting and stabilized thereafter (Kinloch et al. 2008). No clear trend is apparent from our data, at least at this point, that would allow a land manager to project future losses due to WPBR through the life of the plantation. Our results show the value of continued monitoring of these plantations in order to provide managers with information on long-term performance of F_2 stock.

A key question in the management of improved western white pine is how long trees with WPBR will survive; in other words, what proportion of infected F_2 stock might a manager expect to be alive at a certain point in the future? In natural regeneration, WPBR cankers within 12 inches of the stem are likely to reach the stem relatively quickly and produce stem-girdling (lethal) cankers. In theory, resistance mechanisms in F_2 stock, while not entirely preventing infection, may inhibit WPBR infections thereby preventing or slowing tree mortality. However, Kinloch et al. (2008) reported that tolerance, or the ability to survive with WPBR infections,

was very low in improved western white pine from Idaho. Our monitoring data indicate that there is a high probability of death in F_2 infected with WPBR for 11 or more years (0.95); therefore, there is little indication that F_2 stock, once infected, can survive over the long-term.

Incidence of WPBR ultimately depends on many interacting factors. These include: the genetics of both the host and pathogen; presence of the alternate host(s); microclimatic conditions as they affect spore development, dispersal, and germination; and host physiology and morphology. As a result of these interactions, infection and mortality vary from year to year and from stand to stand. The initial goal of this study was to establish monitoring plots in plantations with high WPBR hazard, although the plantations varied in rust hazard whether it was estimated based on *Ribes* density or rust index (Mathiasen and Schwandt 1993). After the 11-year monitoring period reported here, the 20 plantations display a wide range of infection levels, from 0 to over 90%. All F_2 stock planted in the IDL and USFS plantations monitored in this study came from the Bingham Seed Orchard in Moscow, Idaho; the F_1 stock came from the Sandpoint Seed Orchard, which is no longer in operation. Since the F_2 stock in all plantations originated from the Bingham Seed Orchard these varying levels of WPBR infection (0-84%) may indicate that the plantations represent differences in environmental conditions and (or) stand-management histories (Muller 2002). This may allow future refinement of WPBR hazard models, which to this point have failed to capture the variability inherent in operational plantations (Hagle et al. 1989, Muller 2002, Rust 1988).

Care must be taken when describing the results of plant breeding programs, particularly in regard to use of the terms "resistant" and "immune." In the language of plant pathology, "resistant" refers to a host (i.e. - western white pine) that possesses qualities that hinder the development of a given pathogen (i.e. - *C. ribicola*), resulting in little or no infection of a host (Agrios 1997). "Immune," on the other hand, refers to a host that cannot be infected by a given pathogen (Agrios 1997). The results from this monitoring effort may indicate that the stock could be more accurately referred to as having "improved rust resistance," since it performs much better against WPBR than either F_1 stock or naturals but still experiences considerable infection and mortality. Operationally, however, F_2 stock is still described as "resistant," although the level of resistance varies widely among plantations.

These plots have thus far provided useful information on infection by and mortality from WPBR. However, many questions remain including:

1) Can we predict the level of WPBR infection in F_2 western white pine plantations?
2) What level of mortality due to WPBR can managers ultimately expect through the life of a plantation of F_2 stock? and
3) Can a revised hazard model for WPBR be developed to assist managers in writing stand-level management prescriptions?

Remeasurement of these monitoring plots is relatively inexpensive compared to the cost of installation and maintenance that has gone into them. We expect the value of these plots to increase as we add further, concurrent remeasurement data that will help to answer the above questions.

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Appendix A

State of Idaho

Monitoring Genetically Improved Western White Pine Plantations for Blister Rust Infection in Northern Idaho - Idaho State and Forest Service Lands. Establishment and Preliminary Results: 1991-1992

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INTRODUCTION

Western white pine with genetically improved blister rust-resistance have been operationally outplanted on Idaho state and Forest Service lands since the late 1970's. However, there has been no consistent, long-term monitoring of the field performance of the first (F_1) or second (F_2) generation rust-resistant operational plantations. Data from test plantations containing blocks of various western white pine stock types from wild to F_2 have yielded data indicating that survival of F_2 trees may be greater than originally expected (Goddard et al. 1985). However, at present there is some concern that rust-resistant stock planted on sites with high rust hazard may not be performing as well as earlier reports suggested. Therefore, this project was initiated to further evaluate the field performance of rust-resistant western white pine in operational plantations on federal and state lands in northern Idaho.

The major objective of this project is to monitor white pine blister rust infection in operational F_1 and F_2 plantations, particularly in high rust hazard sites. Permanent plots established in plantations representing different levels of hazard to blister rust infection (Hagle et al. 1987) will be revisited at approximately 3-5 year intervals to document any changes or trends in rust infection and pine mortality. Young plantations (3-9 years) are being selected for monitoring because it is easier to distinguish between naturally regenerated and planted seedlings and to more accurately identify causes of mortality as they occur. In young plantations natural seedlings can usually be identified based on their age or position relative to the spacing pattern of the planted stock. In older plantations, many older dead seedlings may completely disappear and can not be included in mortality estimates. This report summarizes the work accomplished during the first two years of the project.

METHODS

Plantations to be sampled were selected based on records maintained by Ranger Districts and State Supervisory Areas. Factors used to select plantations included: stock type (F_1 or F_2), plantation age and location, acres planted, and estimates of the number of western white pine planted. Plantations were then ground-checked to ascertain if they would be suitable based on actual western white pine densities.

The following data were recorded on field data forms for each plantation:

1. Supervisory Area or National Forest and Ranger District
2. Plantation Name and Unit Number
3. Plantation Number (Assigned by this study)
4. Location (Township, Range, Section, and Quarter Section)
5. Date Established and Acres Planted
6. Species Planted and Stock Type (F_1 or F_2)
7. Sampling Design: Distance between transects and distance between plots.

The sampling design consisted of establishing 0.05 acre circular plots placed approximately two to six chains apart along a line transect. Transects were spaced at one to four chain intervals within each plantation. Each plot was marked by placing a metal or wood stake at the plot center. If no western white pine were located within a plot boundary it was rejected and another plot selected. A minimum of 100 western white pine were sampled in each plantation whenever possible. In some plantations it was not possible to sample 100 western white pine because the white pine were planted in mixtures with other species and white pine densities were low. Additional plots may be added at a later date to increase the sample size in those plantations.

The following data were recorded on field data forms for each circular 0.05 acre plot sampled:

1. Plantation Number (as assigned by this study)
2. Transect Number
3. Plot Number
4. Tree Number
5. Tree Height (nearest 0.1 foot)
6. Age (whorls)

7. Infected with blister rust (0 - no, 1 - yes, 2 - maybe, recheck)
8. Live/Dead (0 - live, 1 - dead)
9. Planted/Natural (0 - planted, 1 - natural, 2 - uncertain)

The initial line transect in each plantation was started from a randomly selected point. The direction (compass bearing) of the initial transect was recorded. In IDL plantations additional line transects were run parallel to the first transect starting from a base line that ran approximately parallel to the plantation boundary. The base line direction (compass bearing) was recorded on the plot form. The starting points for additional line transects were spaced at two to four chain intervals along the base line and were monumented with a metal or wood stake.

To assist with relocating the initial starting point a reference point (usually a tree) was selected near the main road leading to the plantation. The reference point was painted with a yellow band at breast height (4.5 feet above ground level). The direction (compass bearing) and distance to the starting point for the initial line transect from the reference point were also recorded. If the distance to the starting point was greater than 5 chains, supplemental reference points (usually trees) painted with a yellow band at breast height were used to help when relocating the starting point for the base line and initial transect line. The bearing and distance between each reference point were recorded also.

In Forest Service plantations, plots were established along line transects or randomly placed throughout the plantation. The bearing and distance from the first plot to a reference point (usually a tree) was recorded. The bearing and distance to each sequential plot was recorded along with bearings to the initial reference point. To further facilitate plot relocation, bearings and distances to nearby plots and additional reference points were recorded also.

A sketch map of the plantation listing or indicating approximate locations of major roads, reference points, starting points, base lines, line transects, plots, distances, and compass bearings was completed for each plantation.

To save time, planted seedlings were not tagged, but were measured in a clockwise direction starting with the seedling nearest the plot center and a due north azimuth bearing. Seedlings will be relocated using their past height and the sequence in which they were recorded on field data forms.

Natural seedlings were identified based on their age and position relative to the spacing pattern of planted stock. In young plantations planted stock may have evidence of vermiculite near their base and natural seedlings will not. If a seedling could not be identified as natural or planted with any certainty, it was coded as uncertain (code 2) and these seedlings were not be used in the data summaries. In addition, no seedlings (live or dead) that could not be positively identified as either blister rust-infected or not infected were used in the data summaries.

Each plantation was examined after June 15 to determine *Ribes* population densities within each plot. Results were recorded by species (*Ribes viscosissimum*, *Ribes lacustre*, and *Ribes hudsonianum*) on the plot data forms. In IDL plantations the number of *Ribes* bushes was counted on the 0.05 acre plots used to sample rust infection. In Forest Service plantations *Ribes* counts were made on 1/300 acre circular plots nested inside of the 0.05 acre plots.

An estimate of the density of *Ribes* populations near the IDL plantations was made by running a line transect due north, west, south, and east from the midpoint of each side of the plantation for a distance of approximately 900 feet. A 1/300 acre circular plot was established every 100 feet along each line transect. The number of *Ribes* bushes for each species within each 1/300 acre plot was recorded. Estimates of *Ribes* seed density in the soil were not made in the plantations sampled.

In order to calculate an estimate of rust index (Hagle et al. 1989) a sample of at least 50 wild-type western white pine were sampled outside,

but within 900 feet, of the plantations whenever possible. These western white pine were at least ten years old but less than 35 feet in height. The height (nearest 0.1 foot), number of whorls, and number of rust cankers was recorded for each of these trees. These trees were sampled by traversing the area around the plantation until at least 50 trees were sampled.

Rust index is based on the number of cankers accumulated on a tree divided by the accumulated target area (number of needles) that was exposed to rust infection over the life of the tree. The individual rust indexes for the sampled western white pine are summed and divided by the total number of trees sampled to obtain the average rust index for any given site. The rust index was calculated using a rust index computer program developed by Geral McDonald, USDA Forest Service, Intermountain Experiment Station, Moscow, ID.

If at least 50 wild-type western white pine were not located near the plantation, rust hazard was estimated based on the *Ribes* population surveys in or around the plantations only. This was necessary for all of the plantations located on Forest Service lands.

A second sampling design was used during 1992 in four IDL plantations that appeared to have areas with high rust infection rates (East Side 2, 3, 4, and 5). A strip transect was run through the areas with high rust infection and the same data (except plot number) recorded as for the circular 0.05 acre plots. Strip transects varied in width and length depending on the size of the area with the heavy rust infection. In addition, these plantations were sampled more intensively in 1992 using line transects and 0.05 acre circular plots (20-25 plots/plantation).

Table 1. Blister rust infection of F1 and F2 western white pine in IDL and Forest Service plantations sampled in 1991-92.

Plantation	Year[1]	Age[2]	Stock Type	# Plots	Trees[3]	% Live Infected[4]	% Dead Infected[5]	Total % Infection[6]
All the Way	91	7	F2	8	101	0	0	0
Halfway	91	9	F2	8	132	1	0	1
Paradise Valley	91	7	F2	10	169	0	0	0
East Side 1	91	5	F2	4	65	3	0	3
East Side 2	91	5	F2	4	52	19	6	25
	92	6	F2	20	248	14	12	26
East Side 3	91	5	F2	4	55	22	22	44
	92	6	F2	20	206	17	23	40
East Side 4	91	5	F2	4	61	21	13	34
	92	6	F2	20	302	15	21	36
East Side 5	91	5	F2	4	68	22	3	25
	92	6	F2	25	209	11	14	25
East Side 6	91	5	F2	4	51	4	0	4
Varnum 11	92	3	F2	10	99	1	0	1
Varnum 23-2	92	4	F2	12	97	3	0	3
Copper-Gimlet 2	92	6	F2	9	69	3	23	26
Copper-Gimlet 21	92	9	F2	14	161	18	14	32
Copper-Gimlet 1	92	6	F2	25	155	35	12	47
Varnum 23-1	92	4	F1	13	108	35	16	51
Varnum 2	92	4	F1	13	103	59	7	66

1 – Year of plantation evaluation.

2 – Plantation age at evaluation.

3 – Number of trees sampled.

4 – Percent of sampled, live trees with WPBR infection.

5 – Percent of sampled, dead trees with WPBR infection.

6 – Percent of all sampled trees with WPBR infection.

RESULTS

Nine IDL plantations were sampled during 1991-92: three in the Pend Oreille Supervisory Area and six in the Priest Lake Supervisory Area. All of the IDL plantations represented F_2 rust-resistant western white pine stock. Seven Forest Service plantations were sampled in 1992. Two of these plantations were F_1 stock and the remainder were planted with F_2 stock.

Seven of the 14 F_2 plantations we sampled had less than 5 percent rust infection, including two IDL plantations that had no infection. Five other F_2 plantations had between 25 and 33 percent infection. Two F_2 plantations had over 40 percent infection (Table 1). The two F_1 plantations had the highest levels of blister rust infection; 51 and 66 percent total rust infection, respectively (Table 1).

The total rust infection levels for the more intensive surveys (20-25 plots/plantation) completed in East Side 2-5 in 1992 were similar to those of the 1991 surveys (Table 1). Mortality associated with blister rust ranged from none in seven of the plantations to just over 20 percent in East Side 3, East Side 4, and Copper-Gimlet 2 (Table 1). The other plantations had 7-20 percent mortality associated with blister rust infection.

Rust hazard based on *Ribes* population surveys was very low or low for most of the plantations with no blister rust or very low (less than 5 percent) rust infection (Table 2). Two plantations (Varnum 11 and Varnum 23-2) had low levels of rust infection but occurred on high rust hazard sites (Table 3).

Rust indexes for three of the IDL plantations surveyed during 1991 indicated those sites also had low rust hazard ratings using the rust index method (Table 2). Because it was not possible to locate an adequate number of wild-type western white pine near each of the East Side plantations, wild-type western white pine within 900 feet of East Side 1-3 had to be used to calculate a rust index for all of the plantations.
Because the plantations were within a half mile of each other this approach is probably valid (personal communication with Geral McDonald, Intermountain Research Station, Moscow, ID). Even though most (73 percent) of the wild-type western white pine sampled had more than one rust canker, the rust hazard based on rust index for these units was only moderate. An adequate number of wild-type western white pine could not be located near the Forest Service plantations, so rust hazard estimates for those plantations were based on *Ribes* population densities within the plantations (Table 3).

Table 2. Rust hazard of IDL plantations based on *Ribes* population surveys and rust index.

Plantation	Plots		Line Transects		Strip Transects		Rust Index	
	Ribes[1]	Rust hazard	Ribes[1]	Rust hazard	Ribes[1]	Rust hazard	Index	Rust hazard
All the Way	0	Very low	0	Very low	--	--	0.0012	Low
Halfway	0	Very low	0	Very low	--	--	0.0012	Low
P. Valley[2]	0	Very low	17	Low	--	--	0.0001	Low
East Side 1	15	Low	10	Low	--	--	0.0284	Moderate
East Side 2	203	High	270	High	787	High	0.0284	Moderate
East Side 3	355	High	140	High	534	High	0.0284	Moderate
East Side 4	324	High	175	High	516	High	0.0284	Moderate
East Side 5	204	High	85	Moderate	496	High	0.0284	Moderate
East Side 6	16	Low	15	Low	--	--	0.0284	Moderate

1 – *Ribes* density is on a per acre basis.

2 – Paradise Valley.

During 1992, strip transects were used to sample areas within the four East Side plantations that had high levels of blister rust infection. Total rust infection in the strip transects ranged from 45-55 percent (Table 4). Rust infection and mortality in these areas was greater than the results based on surveys of the entire plantations using 0.05 acre plots spaced at regular intervals (compare Tables 1 and 4). Although *Ribes* population densities were also higher within the strip transects (Table 4), rust hazard was rated as high.

DISCUSSION

Where rust hazard was rated as low or very low, based on *Ribes* population densities and rust index, blister rust infection of young F_2 rust-resistant western white pine stock has not occurred or is very low in the plantations we sampled. Presumably the F_2 rust-resistant western white pine should continue to experience little, if any, rust infection in these areas. However, Hunt and Meagher (1989) reported that F_2 rust-resistant western white pine from

Table 3. Blister rust infection and rust hazard based on *Ribes* densities for each plantation sampled in 1991-1992.

Plantation	Stock Type	Percent Infection	*Ribes* Density[1]	Rust Hazard
All the Way	F2	0	0	Very low
Paradise Valley	F2	0	0	Very low
Halfway	F2	1	0	Very low
Varnum 11	F2	1	223	High
Varnum 23-2	F2	3	450	High
East Side 1	F2	3	15	Low
East Side 6	F2	4	16	Low
East Side 5	F2	25	204	High
Copper-Gimlet 2	F2	26	5780	Very high
East Side 2	F2	26	203	High
Copper-Gimlet 21	F2	32	150	High
East Side 4	F2	36	324	High
East Side 3	F2	40	355	High
Copper-Gimlet 1	F2	47	4020	Very high
Varnum 23-1	F1	51	1223	Very high
Varnum 2	F1	66	992	High

1 - *Ribes* density is on a per acre basis.

Table 4. Blister rust infection of rust-resistant western white pine and rust hazard in strip transects sampled in 1992.

Plantation	Trees[1]	% Live Infected[2]	% Dead Infected[3]	% Total Infection[4]	*Ribes* Density[5]	Rust Hazard
East Side 2	177	19	36	55	787	High
East Side 3	317	17	28	45	534	High
East Side 4	630	19	26	45	516	High
East Side 5	151	19	26	45	496	High

1 – Number of trees sampled.

2 – Percent of sampled, live trees with WPBR infection.

3 – Percent of sampled, dead trees with WPBR infection.

4 – Percent of all sampled trees with WPBR infection.

5 – *Ribes* density is on a per acre basis.

Idaho, grown at a low rust hazard site in British Columbia, had suffered losses as high as 75 percent in 12 years. They suggested this high rate of infection may be due to differences in rust virulence or environmental conditions found at the British Columbia site. Therefore, we will continue to monitor plantations established in low rust hazard sites, but only at five year intervals.

Rust infection was less than 5 percent in two of the Forest Service F2 plantations (Varnum 23-2 and Varnum 11) even though rust hazard was estimated as high based on Ribes densities within the plantations. These two cases may indicate that F2 rust-resistant western white pine can perform well in high rust hazard sites in northern Idaho. However, in several of the F2 plantations we sampled the rate of rust infection was much higher. The reasons for the higher rates of rust infection are not yet clear, but may be related to the high Ribes population densities coupled with environmental conditions present in those plantations. Another possibility is that the most susceptible individuals are being rapidly infected during "wave" years when environmental conditions are highly favorable for rust infection. Once the most susceptible pines are infected and eliminated from the population, rust infection levels and mortality should decrease. In F2 plantations with high infection levels, one or more wave years may have already occurred even though the plantations are young.

Based on earlier studies of rust-resistant western white pine performance in northern Idaho we expected the level of infection in the very high and high rust hazard areas we sampled to be lower than our results indicate. Steinhoff (1971) found around 20 percent rust infection after 11-15 years in F_1 rust-resistant western white pine planted in two high rust hazard areas. Bingham et al. (1973) reported that an average of only 12 percent of the F_2 and 31 percent of the F_1 rust-resistant western white pine they field tested in a high rust hazard area were infected after three years. After seven years at the same test site, F_1 stock was 47 percent infected with 9 percent mortality due to blister rust, F_2 stock was 27 percent infected with 4 percent dead (Bingham 1983). Goddard et al. (1985) found infection rates as high as 48 percent for F_1 stock after 20-25 years of exposure to blister rust in a very high rust hazard area. They found less rust infection on F_1 stock (31-34 percent) exposed for the same time period in two high rust hazard areas.

The F_1 plantations we sampled in very high rust hazard locations are experiencing higher rust infection rates than those reported above. Both of the F_1 plantations we sampled had rust infection levels over 50 percent. The highest level of rust infection we found was in the Varnum 2 plantation with 66 percent infection only 4 years after the plantation was established. Additional F_1 rust-resistant western white pine plantations established in very high rust hazard areas should be sampled in order to determine if this is a widespread situation.

Although rust infection of F_2 stock was less than that of the F_1 stock we sampled, we are still concerned about some of the high infection levels we measured in F_2 plantations. For example, in a strip transect in East Side 2 plantation an infection rate of 55 percent accompanied by 36 percent mortality seems excessively high for a six-year-old F_2 plantation. Although *Ribes* population densities are high where this level of infection was measured, the *Ribes* densities were not at a level that would put the area into the very high rust hazard category. Other factors, possibly the extremely moist conditions that prevail in the plantation, may be contributing to the high level of rust infection. Furthermore, since the large majority of infected seedlings only had one canker it is probable that most of the rust infection occurred during a single wave year when environmental conditions were highly favorable for rust infection. The wave year probably occurred early in the life of the plantation because many of the infected seedlings already have lethal stem cankers or have died because of rust infection.

Another consideration when comparing rust infection rates is that the high levels of rust infection (45-55 percent) detected using strip transects in four of the East Side plantations

were based on a highly biased sampling method. The samples were purposely taken where heavy rust infection was observed within the plantations. However, three of the random-start, systematic samples of these plantations resulted in rust infection levels of greater than 35 percent. Even if some of the infected seedlings survive, it is unlikely that the 65 percent survival rate for F_2 stock predicted by Bingham (1983) will be achieved in these four plantations.

Based on other reports (Hunt and Meagher 1989) and our preliminary results, there appear to be valid reasons for some concern about how well F_2 rust-resistant western white pine are performing in northern Idaho, particularly in high or very high rust hazard areas. We plan to monitor the plantations we sampled in 1992 in the high and very high rust hazard areas at three year intervals to document changes in infection levels. If little or no additional infection occurs in the F_2 plantations, then the hypothesis that only the susceptible individuals are being infected and quickly eliminated may be valid. However, if rust infection levels continue to increase the reasons need to be ascertained, including examining the possibility of the presence of new and/or more virulent strains of *Cronartium ribicola* in northern Idaho. The possibility of more virulent rust strains has already been reported elsewhere (McDonald et al. 1984; Hunt and Meagher 1985).

We will sample additional F_1 and F_2 plantations located in very high and high rust hazard sites in 1993. In addition, we will sample any F_1 or F_2 rust-resistant western white pine plantations where unusually high levels of rust infection are observed. Since our preliminary results indicate that F_2 plantations located in low rust hazard areas have low levels of infection, only a few additional F_2 plantations in low rust hazard areas will be added to our monitoring effort in 1993 or 1994.

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